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Improvement of shape stability by high-temperature treatment of Norway spruce Effects of drying at 120 °C with and without restraint on twist

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Abstract During drying, timber changes its shape mainly due to shrinkage anisotropy, radial differences in longitudinal shrinkage and spiral grain. The warp, causing severe downgrading of the timber, can be reduced by restraint and appropriate climate treatments of different types. The research presented here is part of a larger project on the improvement of shape stability of Norway Spruce (Picea abies) by high-temperature treatment. In this part, a method for determining twist as well as results for a drying temperature of 120 °C are presented. The effects of presteaming, drying and steaming with and without restraint on the size of twist in Norway Spruce were investigated in laboratory scale. Short-term twist-reducing effects as well as the permanency of the reduced distortions in subsequent moisture cycling were investigated. Results show a clear dependency of twist on the distance from the pith. Furthermore, the twist is reduced in restrained specimens sawn close to the pith. This effect is permanent even after exposure to subsequent moisture cycling.

Verbesserung der Formstabilität von Fichte (Picea abies) durch Hitzebehandlung
Effekt des Trocknens bei 120 °C mit und ohne Belastung auf die Verdrehung

Zusammenfassung Während der Holztrocknung treten Formänderungen des Holzes hauptsächlich aufgrund der anisotropen Schwindung, der radial unterschiedlichen longitudinalen Schwindung und des Drehwuchses auf. Die zu großer Deklassierung führenden Verformungen können durch Belastung während der Trocknung und geeignete Trocknungsprogramme vermindert werden. Die hier vorgestellte Forschungsarbeit ist Teil eines größeren Projektes über die Verbesserung der Formbeständigkeit von Fichte (Picea abies) mit Hilfe von Hochtemperaturtrocknung. Es werden Methoden zur Bestimmung der Verdrehung und Ergebnisse für eine Trocknungstemperatur von 120 °C diskutiert. Die Wirkung von Dämpfen, Trocknung und Konditionierung mit und ohne äußerer Belastung auf die Verdrehung wurde an Fichte im Labormaßstab untersucht. Sowohl die kurzfristige Verringerung der Verdrehung als auch die Beständigkeit dieser Verbesserung während Feuchtewechsel wurden untersucht. Die Ergebnisse zeigen eine deutliche Abhängigkeit der Verdrehung vom Abstand von der Markröhre. Die Verdrehung konnte in marknahen, eingespannten Proben verringert werden. Dieser Effekt bleibt auch nach mehreren Feuchtewechseln bestehen.

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Abbreviations

MC	moisture content
EMC	equilibrium moisture content
RH	relative humidity
LT-drying	low-temperature drying
HT-drying	high-temperature drying

1 Introduction

Shape stability is very important for the use of wood as an engineering material in competition with materials such as concrete and steel, which do not exhibit shape stability problems. One way to create a more stable material is to modify the timber drying, since distortion is mainly caused by the anisotropic and heterogeneous structure of the material, inducing non-uniform shrinkage during drying.

Distortions associated with drying can be reduced by different methods. One is the use of high temperature which leads to plasticization of the timber and can, in combination with external restraint or top-loading, reduce distortions. The effectiveness of this strategy is, however, not well known for Scandinavian species such as Norway spruce (Picea abies). Furthermore it is not known to what extent such quality improvements remain after subsequent exposure to moisture variations.

Research on shape stability most often concentrates on the reasons for distortion during drying. The warp is mainly dependent on spiral grain angle, annual ring curvature, shrinkage anisotropy and radial differences in longitudinal shrinkage. Shape

stability is most often investigated at low drying temperatures and sometimes even for subsequent moisture changes, see e.g. the review given by Johansson (2002).

Research on high-temperature (HT) drying shows that the shape stability can be improved in comparison to low-temperature (LT) drying, but no consistent results about the effectiveness of this improvement are given (Mackay 1973, Price and Koch 1980, Morén and Sehlstedt-Persson 2001). Most of the research on HT-drying has been limited to drying at about 100 °C to 130 °C. Warp in Slash Pine (Pinus elliottii) dried at 145 °C and 200 °C was investigated (McNaught and Gough 1995), but no dependency of the size of warp on the temperature level could be shown. A disadvantage with high temperature treatment is the potential reduction of important timber properties, caused by elevated temperatures, revised e.g. by Salamon (1969).

Drying under restraint has been investigated both for low and high drying temperatures (e.g. Weckstein and Rice 1970, Arganbright et al. 1978) but does not show a consistent dependency of warp on the temperature level or drying scheme. Different restraint methods like even or serrated stickers (Koch 1974), sticker distance and different load levels (Simpson 1982) have been investigated and usually the better the restraint, the lower are the drying deformations. However, mechanical restraint and loading does not reduce all kinds of warp equally effectively.

The main purpose with the present study is to investigate the twist reduction of laboratory-size specimens of Norway Spruce dried at high temperature with and without external restraint. In this paper, specimen preparation, drying scheme, restraining and measuring methods are described together with results for a test series dried at 120 °C.

2 Materials and methods

2.1 Specimen preparation

To produce specimens, logs were cut from 5 trees of Norway Spruce, designated A to E, taken from Asa experimental forest in Southern Sweden. The trees selected are about 100 years old and did not show severe defects in the forest. They were felled and cut into short logs in November 2002 at temperatures below the freezing point, wrapped in plastic and transported to Lund where they are stored in a freezer room at −4 °C. It is assumed that no drying took place during the time between cutting and storage. From each of the trees, five short logs of about 0.4 m length were sawn at 1.2 m, 5.9 m, 8.9 m, 11.9 m and 14.9 m above the ground (designated 1 to 5, respectively). All the test specimens were sawn according to the same sawing scheme, see Fig. 1. The pith is marked on butt and top end of the log, from which a 40 mm thick slice containing the pith in its mid is sawn. From the remaining two circle segments, two 40 mm-slices are sawn perpendicular to the first slice in a way that their centrelines pass through the pith. From the slice containing the pith, a 50–60 mm long slice is sawn to investigate annual ring width and the spiral grain angle. The rest of the slice is sawn into 20 mm wide, 300 mm long sticks, which have their main axis parallel to the pith and the annual rings almost parallel to the wide face (flat-sawn). One of these specimens contains the pith in its mid. The two remaining slices are also sawn into 20 × 40 × 300 mm sticks. Until testing starts, the specimens are wrapped in plastic and stored in a freezer at −2 °C to 0 °C. A total of 166 specimens were investigated in this study.

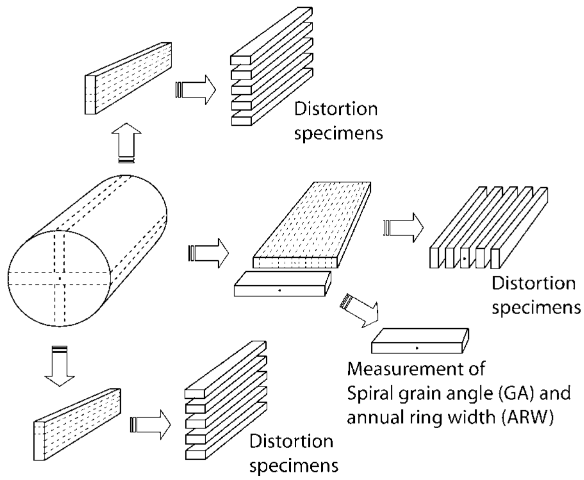

Fig. 1 Sawing the specimens from a short log
Abb. 1 Einschnitt der Prüfkörper

2.2 Laboratory kiln drying and moisture cycling

The drying tests in this project are carried out at three temperatures levels: 80 °C, 120 °C and about 170 °C. To compensate for possible defects and natural variation, one short log from each of the trees was assigned to a certain temperature level. To distribute possible height effects, logs sawn at the same heights were distributed evenly on the temperature levels. At 120 °C, logs A-1, B-2, C-3, D-4, E-5 and C-1 were tested.

Half of the specimens are restrained during the drying process. Both ends of the specimen are clamped in a steel frame provided with springs to ensure a constant restraint for a shrinking and swelling specimen, see Fig. 2. After steaming and cooling phases, the specimens are released.

The drying tests are carried out in a 1 m^3 CTS climate test cabinet. The drying scheme used in the tests consists of 5 phases, each of which is followed by distortion and moisture content (MC) measurement. The specific temperatures and duration of the different phases can be found in Table 1. The treatment starts with presteaming to warm up the specimens without drying and to soften the material, followed by drying. After completed drying, the chamber is opened to cool the specimens down to about 80–90 °C (15 to 20 minutes), which increases their ability to take up water during the following steaming phase (Morén 1994). After one hour of steaming, both temperature and humidity are decreased to provide a half-hour cooling phase before the specimens are removed from the cabinet and measured.

Moisture cycling is carried out after completed drying to investigate the permanency of the twist reduction. During moisture

Table 1 Drying scheme
Tabelle 1 Trocknungsschema

No.	Phase	Dry-bulb temperature [°C]	Wet-bulb temperature [°C]	Duration [h:min]	Final MC [%] (mean value)
1	Presteaming	98	98	1:00	
2	Drying	120	97	4:30	6.2
3	Cooling	80–90	No control	0:15–0:20	
4	Steaming	98	98	1:00	
5	Cooling	98 → 60	98 → 56	0:30	10.7

Fig. 2 Restraining device
Abb. 2 Einspannungs-Vorrichtung

cycling, all specimens are placed on stickers, allowing them to move freely. Three climate rooms with dry climate (20 °C, 30% RH), humid climate (20 °C, 85% RH) and room climate (20 °C, 65% RH), respectively are used to establish different moisture conditions in the specimens. After drying, the specimens are first stored three days at room climate, then seven to ten moisture cycles are carried out, starting with humid climate (giving 13.5% MC), followed by dry climate (9.6% MC). After the cycling, the specimens are once again stored in room climate for three days (11.6% MC) before they are oven dried to 0% MC in a regular oven at 105 °C. Due to the short storage time of 3 days, the equilibrium moisture content (EMC) was not reached in the specimens. However, the largest part of the moisture content change takes place during these 3 days, providing a satisfying moisture content difference between low and high RH. The total time for moisture cycling is 66 days.

2.3 Monitoring distorsions and moisture content

Moisture content and distortions are measured after the different phases of the drying process and every time the specimens

Fig. 3 Measuring rig for measurement of distortions. Fixed points are the cube and the two screws on the left and the screw to the right, which is framed by two LVDTs (in the back and in the front of the screw). A third LVDT is in the middle of the measuring rig
Abb. 3 Messgerät zur Erfassung der Verformungen. Lagerpunkte sind der Würfel und 2 Schrauben auf der linken Seite sowie die Schraube auf der rechten Seite. Die Verformung wird mit den beiden Wegaufnehmern rechts und dem Wegaufnehmer in der Mitte gemessen

are moved from one climate to another in moisture cycling. The moisture content of the specimens was investigated by weighing the specimens during the testing process and comparing with the oven dry weight after completed testing. Distortions were investigated in a measuring rig (see Fig. 3), similar to the one described by Perstorper et al. (2001). The distortions are determined by the displacements in the deformation gauges (LVDTs) for the specimen compared to a calibrated "no-distortion-state" using a straight aluminium beam. The precision of twist angle measurement is ±0.08° at a confidence level of 95%. The measuring error might be cut in half by sanding the surfaces of the specimen that are in contact with the distortion gauges. However, when sanding the surfaces, the temperature increased in the specimen, leading to drying prior to testing, which is undesirable.

3 Results and discussion

In Figs. 4 and 5, results are shown for twist as a function of distance from the pith for specimens that were restrained during drying (called restrained specimens) and specimens that were free to move during drying (called free specimens). The twist angle is defined as the angle of rotation of one end grain surface in relation to the other end grain surface. The twist angle direction is in agreement with the definition by Mishiro and Booker (1988). The twist angle shown here results only from drying; i.e. it is the twist angle change from the initial twist obtained directly after sawing. The permanency of twist by high-temperature treatment is shown in Figs. 6 and 7.

From the data it can be seen that twist angle after drying and 3 days storage in 20 °C/65% RH is partly dependent on the specimen's distance from the pith, see Figs. 4 and 5. For free specimens, the twist angle decreases with increasing distance, see

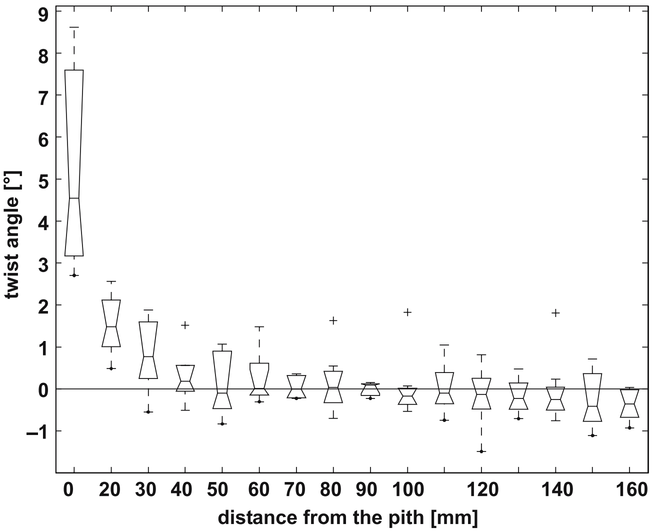

Fig. 4 Box plot for twist angle after drying vs. distance from pith; free specimens. The box has lines at the lower quartile, median, and upper quartile values. The whiskers show the extend of the rest of the data. +-markers represent outliers

Abb. 4 Boxplot des Verdrehungswinkels nach der Trocknung in Abhängigkeit vom Abstand von der Markröhre für freie Prüfkörper. Die Box zeigt jeweils die 25%, 50% und 75%-Fraktile. Die vertikalen Linien geben den Bereich der übrigen Messwerte an. Die +-Zeichen bezeichnen Ausreißer

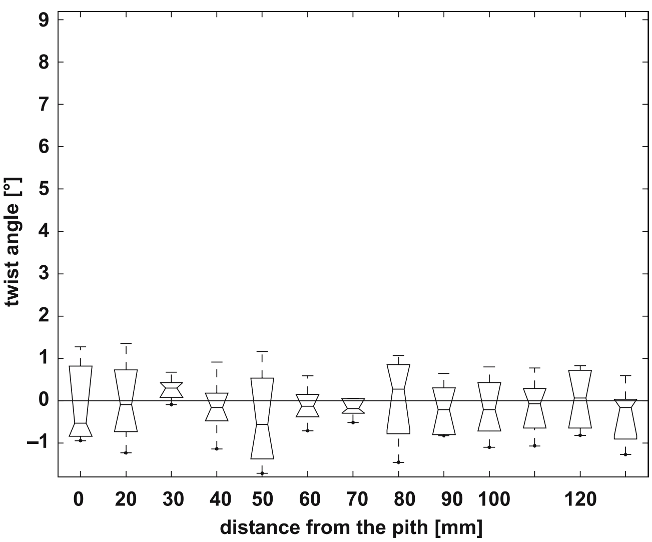

Fig. 5 Box plot for twist angle after drying vs. distance from pith; restrained specimens. The box has lines at the lower quartile, median, and upper quartile values. The whiskers show the extend of the rest of the data

Abb. 5 Boxplot des Verdrehungswinkels nach der Trocknung in Abhängigkeit vom Abstand von der Markröhre für eingespannte Prüfkörper. Die Box zeigt jeweils die 25%, 50% und 75%-Fraktile. Die vertikalen Linien geben den Bereich der übrigen Messwerte an

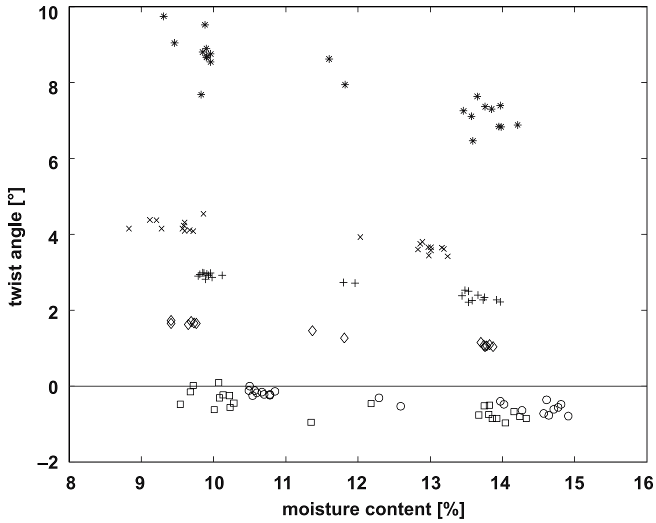

Fig. 6 Twist angle vs. moisture content during moisture cycling in specimens including the pith. $+$, $\times$ and $*$ markers represent free specimens, □, ○ and ◊ markers restrained specimens

Abb. 6 Verdrehungswinkel in Abhängigkeit von der Holzfeuchte während 10 Feuchtewechsel für Prüfkörper mit Markröhre. $+$, $\times$ und $*$ kennzeichnen freie Prüfkörper, □, ○ und ◊ eingespannte Prüfkörper

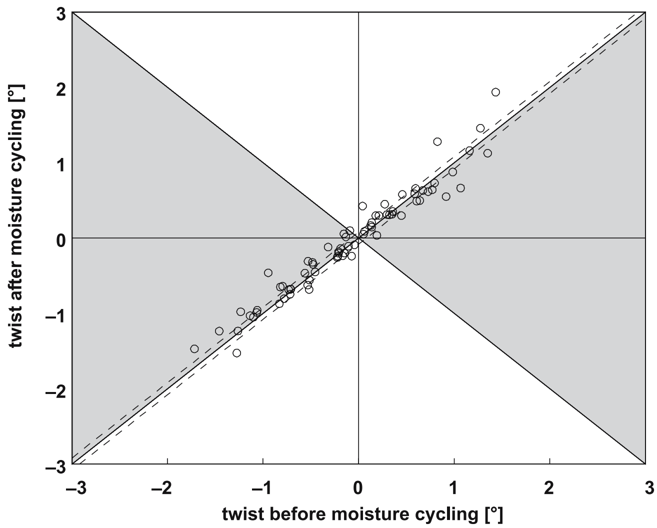

Fig. 7 Twist angle in restrained specimens after moisture cycling vs. before moisture cycling. *Shaded areas* indicate measurements with decreasing twist in moisture cycling. *Dashed lines* indicate measurement accuracy

Abb. 7 Verdrehungswinkel bei eingespannten Prüfkörpern nach bzw. vor den Feuchtewechseln. *Grau unterlegte Bereiche* zeigen Messungen mit abnehmendem Verdrehungswinkel nach Feuchtewechseln. Die *gestrichelte Linie* gibt die Messgenauigkeit an

Fig. 4. However, an analysis of variance shows that at confidence level $\alpha = 0.95$, only specimens sawn at 0 and 20 mm from the pith experience a distance-effect. However, the small size of the central region with excessive twist found in this investigation may be due to the small number of specimens tested and the large scatter obtained. A larger data material would probably show a distance-effect in a larger central region of the log than the one obtained here, as was suggested by Johansson (2002), who also observed severe twist in studs of Norway Spruce sawn near the pith and proposed the studs sawn at 75 mm or less from the pith not be used. Interestingly, restrained specimens do not experience any distance-effect at all, as can be seen in Fig. 5. This lack of ef-

fect would suggest that restraint eliminates the dependency on the distance from the pith by decreasing the twist in twist prone specimens. Also here, a larger data material might have shown some dependency of twist on the distance from the pith.

The twist angle after drying is reduced significantly in restrained specimens sawn near the pith compared to matched free-to-move specimens, see Figs. 4 and 5. A statistically significant difference (at confidence level $\alpha = 0.95$) of twist angles between restrained and free specimens is achieved for specimens sawn to include the pith and sawn at 20 mm from the pith. However, for specimens sawn at larger distances, the restraint gives no significant effect. Restraint effectively reduces the twist due to drying in boards sawn with the centre in the innermost 40 mm of the log. Therefore, to achieve an effective restraint and thereby reduce twist, boards including the pith or those sawn near the pith should always be placed in the bottom of the stack during kiln drying.

The permanency of the twist reduction is shown in Figs. 6 and 7. In Fig. 6, twist is plotted against moisture content for specimens including the pith. The twist angle was measured for 10 moisture cycles between 30% and 85% RH at 20 °C. The figure shows clouds of measurements for different specimens, one marker representing all the measurements on a single specimen. The twist angle is reversible, i.e. there is a certain twist angle difference between high and low moisture content, which tendentially is larger for free specimens (+, × and ∗ markers) than for restrained specimens (□, ◊ and ○ markers). The two measurements between high and low moisture content at about 12% MC were carried out before and after moisture cycling at 20 °C, 65% RH. The small differences between these two values show clearly that the overall tendency for twist in a specimen is not influenced by subsequent moisture changes. In Fig. 7, the permanency of the twist is shown for all restrained specimens, showing twist after moisture cycling versus twist before moisture cycling (an almost similar figure could be plotted for free specimens). Both twist measurements were carried out at the same MC in the specimens. The figures show measurement points for single specimens as well as a line with $f(x) = x$. Measuring points situated in the grey shaded areas indicate that the twist angle decreased during moisture cycling, whereas twist angle increased in moisture cycling for measuring points in the white areas. The dotted lines correspond to the measuring accuracy of the twist measurement. At confidence level $\alpha = 0.95$, it can be shown that there is no significant difference between twist before and after moisture cycling.

As reported in the literature, even for HT-drying, twist is not permanent in moisture cycling, as Haslett and Dakin (2001) showed. Radiata pine dried with a top load of 500 kg m^{-2} at 140 °C and steamed at 100 °C after drying experienced a tendency to increasing twist in subsequent moisture cycling, whereas timber treated with pressure steaming at 150 °C did not experience an increase in twist, but instead, the twist was reduced by at least 25% compared to the conventionally steamed material. However, in the present study the quality improvements on the twist produced by the restraint during drying and steaming remain, thus proving the effectiveness of the combination of high-temperature treatment with restraint.

The twist amplitude in moisture cycling is defined by the largest difference between twist values for low and high moisture contents in the seven to ten moisture cycles. Changes in twist angle up to 3.3° were obtained for pith specimens. However, the mean value of twist change in moisture cycling is 0.46°. For the free specimens, an analysis of variance shows that the amplitude of twist in moisture cycling is significantly larger for specimens sawn to include the pith and sawn at 20 mm from the pith than in specimens sawn at larger distances from the pith. The same applies to the restrained specimens, here significantly larger twist amplitudes are found for specimens sawn to include the pith and at 20 and 30 mm from the pith, compared with specimens sawn at larger distances. However, comparing specimens dried under restraint and without restraint, respectively, no significant difference in twist angle amplitude is found (at confidence level $\alpha = 0.95$).

Overall, the results of this investigation show certain tendencies in the response of timber to kiln drying. Since the investigation showed that specimens sawn at a large distance from the pith are not influenced by the restraint, the experimental procedure was modified to only use specimens sawn not more than 120 mm from the pith in future experiments. Additionally, the specimens are sawn at a decreased number of distances from the pith, using 20 mm steps instead of 10 mm steps. This increases the number of equally treated specimens and therefore leads to improved possibilities of analysis and evaluation. Additionally, extra material sawn near the pith will be obtained from a sawmill to increase the number of specimens.

In order to make it possible to compare the effect of the treatment on different species, further experiments will be carried out to include different larch species that are treated in the same way as spruce. Experiments carried out at both lower and higher temperatures than used in this investigation will reveal the influence of drying temperature on the amount of twist in both spruce and larch wood.

4 Conclusions

Drying at 120 °C and steaming under restraint can effectively improve the quality of the twist-prone specimens sawn near the pith, significantly reducing the twist value. Twist in free specimens varies systematically with distance from the pith. For the material investigated in this study, significant twist was only found in specimens at a maximum distance of 20 mm from the pith. The restraint used in this study reduces the twist of the twist prone specimens (pith specimen and specimens at 20 mm from the pith) to twist angles comparable to specimens sawn at larger distances from the pith. Specimens dried with and without restraint exhibit small reversible changes in twist during subsequent moisture cycling. No accumulated effects were found, which makes the obtained quality improvement permanent, even under subsequent moisture cycling as in-service conditions.

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